AD-A009 724

IMAGE INFORMATION BY MEANS OF SPECKLE PATTERN PROCESSING

Paul H. Deitz

Ballistic Research Laboratories
Aberdeen Proving Ground, Maryland

March 1975

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER BRL REPORT NO. 1772	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER AD-A009 724
4. TITLE (and Subtitle) IMAGE INFORMATION BY MEANS OF SPECKLE PATTERN PROCESSING		5. TYPE OF REPORT & PERIOD COVERED 6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) PAUL H. DEITZ		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS USA Ballistic Research Laboratories Aberdeen Proving Ground, MD 21005		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
11. CONTROLLING OFFICE NAME AND ADDRESS US Army Materiel Command 5001 Eisenhower Avenue Alexandria, VA 22333		12. REPORT DATE MARCH 1975 13. NUMBER OF PAGES 26
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)		15. SECURITY CLASS. (of this report) UNCLASSIFIED 15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Holography
Interferometry
Atmospheric Optics
Scintillation
Coherence

PRICES SUBJECT TO CHANGE

20. ABSTRACT (Continue on reverse side if necessary and identify by block number) (kst)

When a laser beam is reflected from a diffuse surface, a granular scattering distribution is commonly observed, called a speckle pattern. We will discuss some of its ramifications: (1) that this pattern is the time-dependent analogue of the signal used in the classic Hanbury Brown - Twiss stellar interferometer of the 1950's; (2) that this pattern can be processed by standard incoherent optical techniques to yield information pertaining to the object radiance distribution; (3) that this same signal, when processed

Continued on reverse side.

DD FORM 1 JAN 73 1473 EDITION

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

20. ABSTRACT (Cont.)

by coherent-optical techniques, is equivalent to the Gabor on-axis hologram or the Fourier-transform hologram, depending on the specific source configuration; and (4) that signals processed by all of the above techniques are comparatively insensitive to atmospheric turbulence.

An experiment is performed to illustrate the procedure of item (2) and then modified to show assertion (4).

1-a

Destroy this report when it is no longer needed.
Do not return it to the originator.

Secondary distribution of this report by originating or sponsoring activity is prohibited.

Additional copies of this report may be obtained from the National Technical Information Service, U.S. Department of Commerce, Springfield, Virginia 22151.

NTIS	White Section	☐
	Buff Section	☐
		☐
DISTRIBUTION/AVAILABILITY CODES		
Dist.	AVAIL. and/or SPECIAL	
A		

The findings in this report are not to be construed as an official Department of the Army position, unless so designated by other authorized documents.

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

Preceding page blank

I. INTRODUCTION

In 1948, Gabor[1] proposed a two-step imaging process, which has come to be known as holography. In this process an optical record is formed that has the information necessary to create an image. In 1956, Hanbury Brown and Twiss[2] discussed a radically new type of interferometer in which time-averaged irradiance correlation replaces the familiar correlation of electric fields as in, for example, the Michelson interferometer. Following the invention of the laser, Martienssen and Spiller[3] summarized the conditions necessary to obtain spatial and temporal coherence; they demonstrated those criteria experimentally by use of a quasithermal source to form time-varying granular scattering patterns. Shortly thereafter, Goldfischer[4] showed that the statistics of a far-field laser speckle pattern are related to the irradiance distribution over the scattering object.

We submit that the above work, cited merely to typify apparently disjoint studies, is, in fact, unified by a series of fundamental aspects common to each: (1) that the signal utilized in each case is the same whether it be called a hologram, a correlation signal, or a speckle pattern; and (2) that the coherence criteria necessary to form a hologram, to do irradiance correlation (either temporally or spatially), or to observe a speckle pattern are identical.

We assert further that the principal difference between holography and irradiance correlation is simply the manner in which the signal is normally processed: (1) that a speckle pattern can be processed by standard incoherent techniques to yield information pertaining to the object radiance distribution in the sense of the Hanbury Brown - Twiss experiment; but (2) that this same signal, when processed by coherent optical techniques, is equivalent to the Gabor on-axis hologram or the Fourier transform hologram, depending on the specific source configuration; (3) that the ability to reconstruct an image by either approach is dependent on the specific and equivalent source configuration; and (4) that each of these two techniques is comparatively insensitive to the effects of propagation in weak random media.

---

[1] D. Gabor, Nature 161, 777-778 (1948).

[2] R. Hanbury Brown and R. Q. Twiss, Nature 177, 27 (1956).

[3] W. Martienssen and E. Spiller, Am. J. Phys. 32, 919 (1964).

[4] L. L. Goldfischer, J. Opt. Soc. Am. 55, 247 (1965).

Earlier, Goodman[5] compared holographic imaging with coherent light and interferometric imaging with incoherent light. In what follows, we will compare Fourier transform holography and irradiance (fourth-order) correlation, with attention to space and time averages and the source coherence constraints.

II. THE SIGNAL AT THE DETECTION PLANE

We start by writing the well-known form of the Huygens-Fresnel equation for two electric fields sufficiently remote to satisfy the Fraunhofer condition. With reference to Figure 1, the $\underline{\xi}$ and $\underline{x}$ planes are the source and detection planes, where the form of the scalar electric field (used uniformly throughout the report) at the plane of detection can be written

$$\hat{V}(x) = A_1 \iint_{-\infty}^{\infty} V(\underline{\xi}) \exp[-i \frac{k}{R_o} (\underline{x} \cdot \underline{\xi})] d\underline{\xi}. \quad (1)$$

The circumflex indicates a two-dimensional Fourier transform, A_1 is a complex constant, k is the mean wave number of the light, R_o is the distance between the two planes, and the time behavior of the fields has been suppressed. Following Martienssen and Spiller,[3] we construct a quasithermal source at the $\underline{\xi}$ plane; the amplitude distribution over the source plane is constant in time, but random phase variations are introduced by the presence of a ground-glass surface which can be given some angular rotation. At the receiver plane, the electric field is the superposition of all of the individual contributors in the $\underline{\xi}$ plane, taking into consideration the propagation geometry and the random phase given to the source amplitudes by the ground-glass at a particular time.*

The pattern of observation is, of course, the square of the electric field. If the angular velocity of the ground-glass at the source is sufficiently slow that the detection mechanism resolves the time-varying pattern, a speckle pattern will be observed. If not, only the mean irradiance will be detected. Using Equation (1), we write the detection signal as a second-order correlation of fields where

---

[5] J. W. Goodman, J. Opt. Soc. Am. 60, 506 (1970).

*For simplicity, we disregard the finite propagation time.

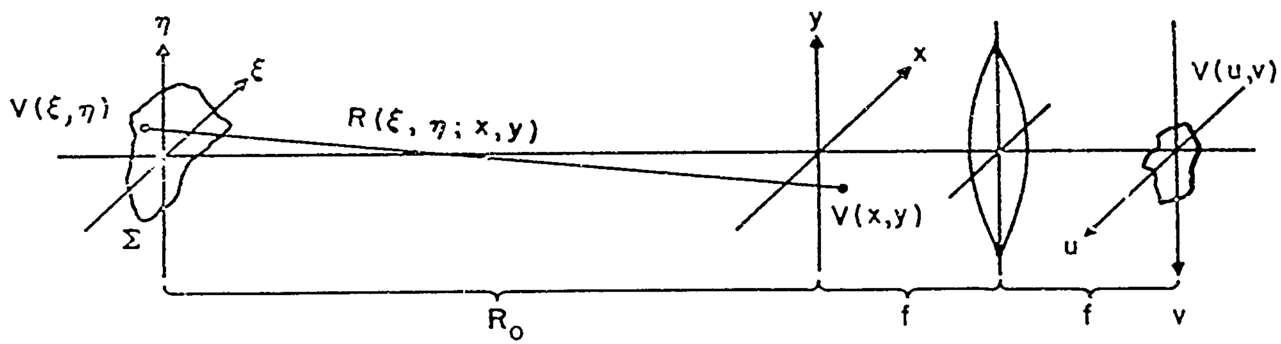

Figure 1. Coordinate axes. Object is located in the $\underline{\xi}$ plane; the $\underline{x}$ plane is located in the far zone of the object. A lens is also in the far zone; the focal length is f, and the $\underline{u}$ plane is the output plane.

$$\langle\hat{V}(\underline{x}_1)\hat{V}^*(\underline{x}_2)\rangle_{(\,)} = A_2\iiiint_{-\infty}^{\infty}\langle V(\underline{\xi}_1)V^*(\underline{\xi}_2)\rangle_{(\,)}\exp[-i\frac{k}{R_o}(\underline{x}_1\cdot\underline{\xi}_1-\underline{x}_2\cdot\underline{\xi}_2)]d\underline{\xi}_1 d\underline{\xi}_2, \qquad (2)$$

and A_2 is a complex constant; the angle brackets denote an average in a sense not yet specified at the position of the unfilled parentheses.

Classically, in the manner of Young's double pinhole experiment, the ergodic hypothesis is invoked and, through the assumption of temporal stationarity, the time average is assumed equivalent to the ensemble average. It is well known that the autocorrelation of a white noise signal takes the form of a delta function. The effect of the ground glass is therefore to prewhiten the scalar field over the source. Given the time-variant nature of the source random phase, the average within the integral of Equation (2) is taken to have the idealized form

$$\langle V(\underline{\xi}_1)V^*(\underline{\xi}_2)\rangle_T = I(\underline{\xi})\delta(\underline{\xi}_1-\underline{\xi}_2), \qquad (3)$$

where the subscript denotes a time average over a period very much longer than the coherence time of radiation. By virtue of the spatial incoherence criteria of Equation (3), the effect of the source prewhitening is to prevent all of the field cross terns within the integral of Equation (2) from contributing to the averaging process following detection. The effect of applying the criterion* of Equation (3) in Equation (2) is to give the well-known Van Cittert-Zernike theorem where

$$\langle\hat{V}(\underline{x}_1)\hat{V}^*(\underline{x}_2)\rangle_T = A_2\iint_{-\infty}^{\infty} I(\underline{\xi})\exp[-i\frac{k}{R_o}(\underline{x}_1-\underline{x}_2)\underline{\xi}]d\xi. \qquad (4)$$

*The criterion of Equation (3), when applied to Equation (2), reduces the dimensionality of the integral by a factor of two. This approach is actually a short-hand method for changing the spatial variables of integration to center-of-mass coordinates and letting the difference variable describe the object spatial coherence. In the incoherent limit, this function goes to a delta function, eliminating one pair of integrals. This approach has been used, for example, by P. H. Deitz and F. P. Carlson, J. Opt. Soc. Am. 63 274 (1973).

Although the field itself cannot be recorded at the detection plane, signals proportional to the field or to some higher-order correlation, can be recorded at the receiver plane. Invoking the ergodic hypothesis in a spatial sense, we can obtain a spatial average to derive certain statistics of interest. We will use this approach later in spatial irradiance correlation.

Martienssen and Spiller,[3] in a simple derivation, showed that the criterion for temporal coherence and the observation of speckles in a light beam is that the time of observation T satisfy the inequality

$$T \ll \frac{1}{\Delta\nu}, \tag{5}$$

where $\Delta\nu$ is the temporal bandwidth of the radiation. If this detector-time-resolution criterion is met, although the speckle pattern may vary in space, it will not vary in time.

III. THE CASE OF HOLOGRAPHY

Having established the conditions necessary for recording a speckle pattern, we now examine the process of coherent signal processing in holography.

As is well known, in the original two-step imaging scheme proposed by Gabor, the object is a transparency in which only a small fraction of the incident wave is scattered. The scattered and unscattered wave portions interfere at the detection plane, where the signal squaring takes place. Because of the necessity of having a strong reference wave (relative to the scattered wave), as well as the difficulty of separating the two resulting images, this scheme, except for special cases, has generally given way to the important modification, suggested by Leith and Upatnieks,[6] of the side-band hologram technique.

Following DeVelis and Reynolds,[7] we wish to summarize the specific case of the Fourier transform hologram, because this construction best represents the class of optical systems with which we are concerned.

---

[6] E. N. Leith and J. Upatnieks, J. Opt. Soc. Am. 54, 1295 (1964).

[7] J. B. DeVelis and G. O. Reynolds, Theory and Applications of Holography (Addison-Wesley, London, 1967), pp. 62-64.

As indicated in Figure 2a, the object appears in the $\underline{\xi}$ plane. We use a lens to perform the Fourier-transform operation to the $\underline{x}$ plane. Thus the total object field can be written

$$\psi(\underline{\xi}) = \delta(\underline{\xi}) + D(\underline{\xi} - \underline{\xi}_0), \tag{6}$$

where the delta function represents the point reference, $D(\underline{\xi} - \underline{\xi}_0)$ represents the object field distribution, and $\underline{\xi}_0$ is the distance between the reference point and the center of the object. The criterion for the magnitude of $\underline{\xi}_0$ will be discussed in a later section. The field at the detection plane is

$$\hat{\psi}(\underline{x}) \propto 1 + \hat{D}(\underline{x}) \exp\left[-\frac{2\pi i}{\lambda f}(\underline{\xi}_0 \cdot \underline{x})\right], \tag{7}$$

where λ is the mean wavelength of the radiation and f is the lens focal length. We now assume that the square-law detection process is arranged proportional to the field amplitude (rather than the irradiance) so that (ignoring constant factors)

$$\begin{aligned} I(\underline{x}) &= |\hat{\psi}(\underline{x})|^2 \\ &\propto 1 + |\hat{D}(\underline{x})|^2 + \hat{D}(\underline{x}) \exp\left[-\frac{2\pi i}{\lambda f}(\underline{\xi}_0 \cdot \underline{x})\right] \\ &\quad + \hat{D}^*(\underline{x}) \exp\left[\frac{2\pi i}{\lambda f}(\underline{\xi}_0 \cdot \underline{x})\right]. \end{aligned} \tag{8}$$

When a coherently illuminated transparency has the transmission characteristics indicated by Equation (8), as shown schematically in Figure 2b, the form of the field at the reconstruction ($\underline{\alpha}$) plane is therefore

$$\psi(\underline{\alpha}) \propto \delta(\underline{\alpha}) + D^*(\underline{\alpha}) \star D(\underline{\alpha}) + D(-\underline{\alpha} - \underline{\xi}_0) + D^*(\underline{\alpha} - \underline{\xi}_0), \tag{9}$$

and $\star$ denotes the operation of convolution. The irradiance in the reconstruction plane is therefore

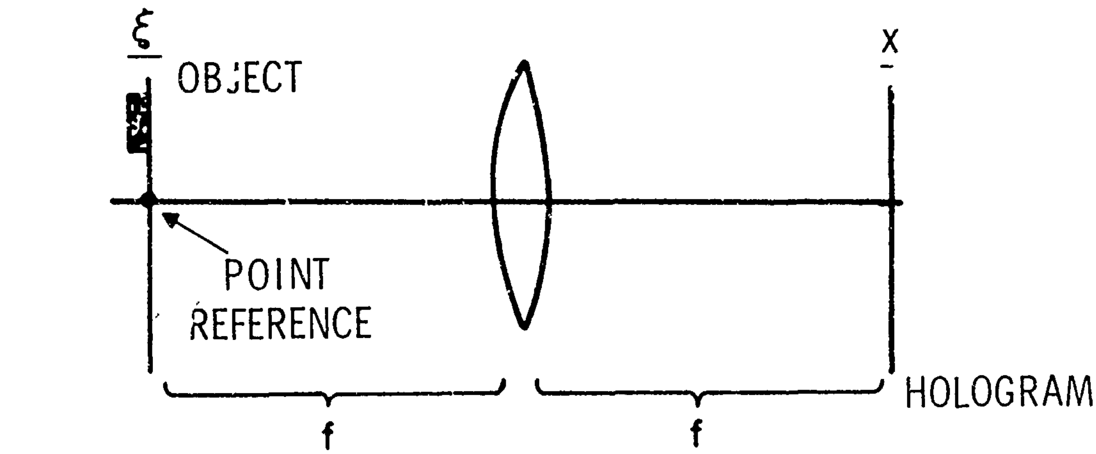

Figure 2a. The formation scheme for a Fourier-transform hologram using a lens.

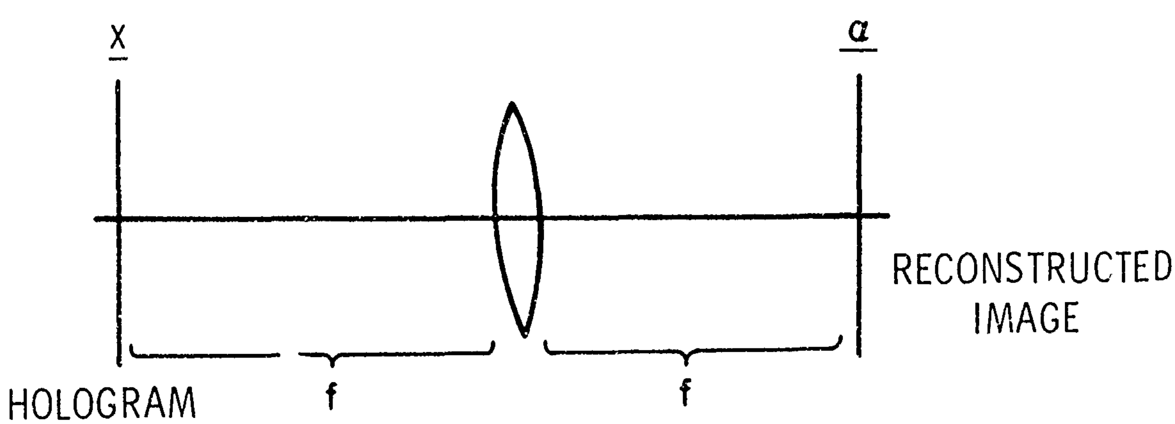

Figure 2b. Reconstruction scheme for a.

$$I(\underline{\alpha}) = |\psi(\underline{\alpha})|^2 \tag{10a}$$

$$= |\delta(\underline{\alpha}) + D^*(\underline{\alpha}) \star D(\underline{\alpha})|^2 + |D(-\underline{\alpha} - \underline{\xi}_0)|^2 + |D^*(\underline{\alpha} - \underline{\xi}_0)|^2. \tag{10b}$$

We note that the Fourier-transform-hologram technique gives three terms. The first is a signal composed of a delta function at the origin, around which appears the square of the convolution of the object field with itself. Under the criterion of spatial incoherence, this term has little utility. However, symmetrically about the origin, a pair of images appears, each the reflection through the origin of the other. Thus the original image has been reproduced twofold. We will return to this point later. An example of this process can be found in Reference 7, page 65.

Figure 3 summarizes the processes involved in Fourier transform holography. The Fourier-transform operations between object and receiver spaces are performed, of course, optically. The rest of the operations show the mathematical procedures for deriving particular results in each space.

IV. IRRADIANCE CORRELATION

Although the approach that follows was not used in the early work of Hanbury Brown and Twiss, the key to the various irradiance correlation schemes can be found in this simplified argument. We refer again to Figure 1 and the description of the movable ground-glass source at the object ($\underline{\xi}$) plane. It can be argued that the field at any point in the receiver plane [described by Equation (1)] consists of a sum of random-amplitude, random-phase, complex phasors contributed by the elementary scatterers in the object. If the size of the scattering area is large enough to include many point scatterers (or if enough elementary coherence areas compose the source), the central limit theorem may be used to show that the electric field in the detection plane is a gaussian random process.

In the Hanbury Brown - Twiss experiment, a broad-band source was used. By the quasithermal-source analogy, this corresponds to a source-coherence time inversely proportional to the angular velocity of the spinning ground glass. In this experiment, the irradiance in the detection plane is sampled at a pair of points, multiplied and averaged with many other such products, sampled in time.

The average that has been defined in the time domain corresponds to a reduced fourth-order correlation in electric field since squared terms appear in the moment calculation. Because the field in the receiver plane is a gaussian function, the well known moment theorem

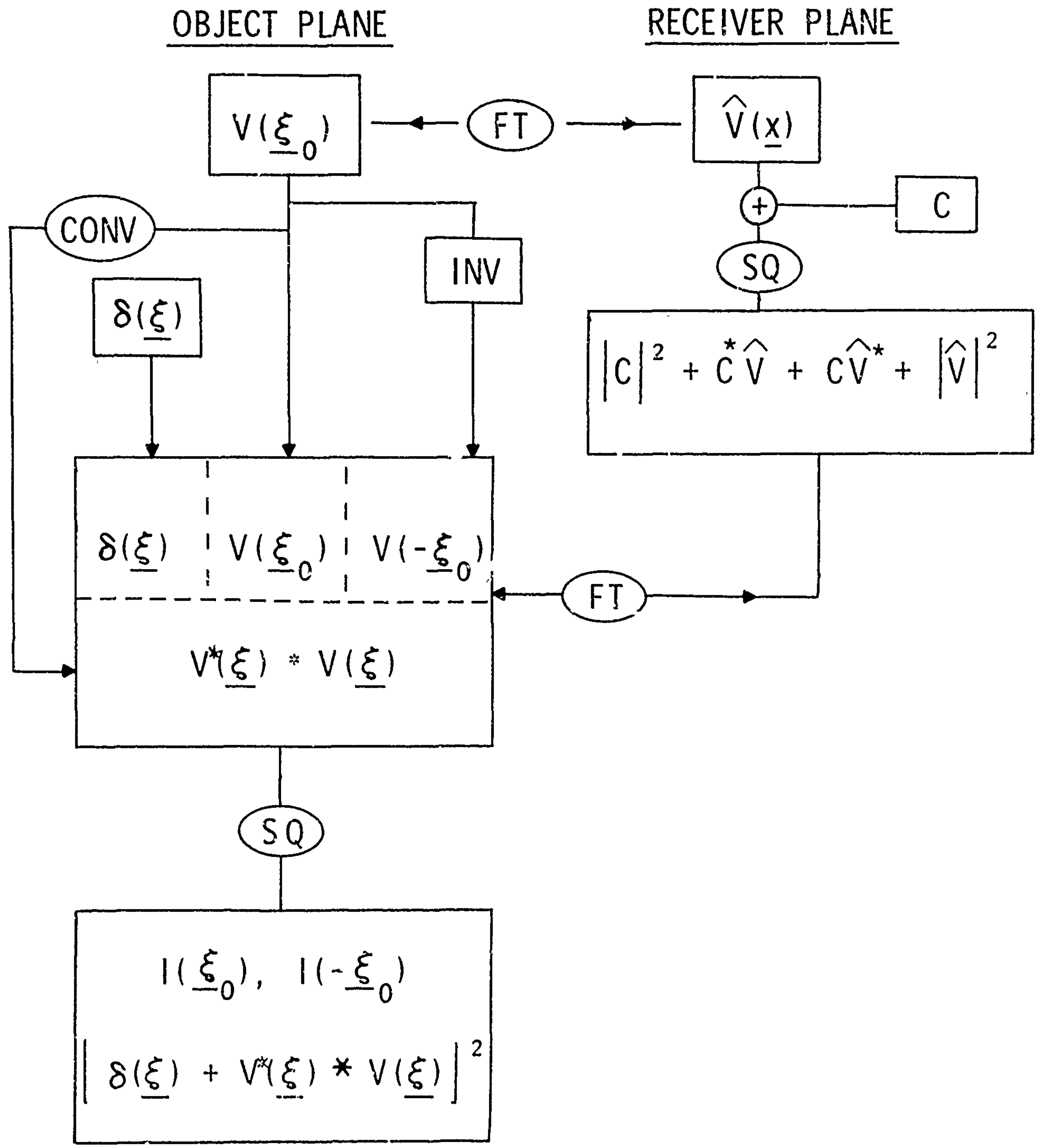

Figure 3. Mathematical relationships for Fourier-transform holography. The Fourier-transform relation (FT) in electric fields (indicated by a circumflex) stems physically from the form of the Huygens-Fresnel equation. CONV (*) indicates convolution; INV, inverse; C, a constant; and SQ, a squaring operation.

can be used to express all higher-order moments in terms of the first and second, where

$$\langle I_1 I_2 \rangle_{(\ )} = \langle I_1 \rangle_{(\ )} \langle I_2 \rangle_{(\ )} + |\langle V_1 V_2^* \rangle_{(\ )}|^2, \qquad (11)$$

and the parentheses indicate the domain in which the averaging process takes place. In the Hanbury Brown - Twiss experiment, of course, the domain of averaging is the time domain. Thus, ignoring constant terms, we can write the fourth-order correlation, expressed by the left-hand side of Equation (11), in terms of the square of the second-order correlation of fields expressed by Equation (4).

Goldfischer[4] derived the relations for the speckle pattern correlation in the detection plane for the case of a monochromatic carrier and a spatially incoherent object. His result, similar to the relationship of Equation (11), was derived by eliminating terms in which random phases appear by a spatial averaging process. Although the average is spatial, the mathematical operation shows great similarity to the temporal process of Hanbury Brown - Twiss;[8] the fundamental equivalence of these two approaches was not mentioned by Goldfischer.

More recently, Deitz and Carlson,* in an effort to extend the Hanbury Brown - Twiss results to the spatial domain, derived similar relations for the case of quasimonochromatic radiation. Under these conditions, the detection-time-exposure criteria become important. However, there is a basic equivalence of their work to Goldfischer's speckle correlation.

In the meantime, Beard[9] performed a correlation experiment, using the rotating ground-glass source in a special configuration that will be discussed later, in which the irradiance signals from a pair of detectors were averaged over time; this average signal was then used to modulate the z-axis of an oscilloscope so that the correlation function could be displayed spatially and processed optically. This approach is a kind of composite of both a time average and a spatial display method.

---

[8] R. Hanbury Brown and R. Q. Twiss, Proc. R. Soc. Lond. Ser. A. 243, 291 (1957). This paper appears in Coherence and Fluctuations of Light, Vol. I, edited by L. Mandel and E. Wolf (Dover, New York, 1970), Eq. (A6).

*See footnote on page 10.

[9] T. D. Beard, Appl. Phys. Lett. 15, 227 (1969).

We note again that Equation (11) relates the irradiance correlation in the detector plane to the square of the second-order correlation of fields. By Equation (4) (and the assumption of spatial incoherence of the source), the second-order correlation of fields is the (generally complex) Fourier transform of the source radiance distribution. The square of this function is the power spectrum. Thus, by the autocorrelation theorem, the Fourier transform of the power spectrum (derived by autocorrelating the far-field speckle pattern) is the autocorrelation of the object radiance distribution. These basic relations for irradiance correlation are summarized in Figure 4.

To illustrate some of these operations, we have performed an experiment, following the procedure used by Goldfischer.[4] Figure 5a shows the image of a pair of crossed Ronchi rulings used for the object. This image was derived in the standard way at the focus of the lens indicated in Figure 1. Because irradiance correlation normally yields the power spectrum, the signal of Figure 5a was coherently processed to give the power spectrum displayed in Figure 5b. Using the object of Figure 5a together with ground glass to achieve spatial incoherence, we recorded the ($\underline{x}$ plane) speckle signal shown in Figure 6a. When this signal is processed by incoherent optical correlator,* the function shown in Figure 6b results. This is the (low-frequency portion of) power spectrum of the object-radiance distribution and can be compared directly with the image of Figure 5b. Under the condition of imaging without a distorting medium, the signal of Figure 6b is somewhat inferior, showing some spatial noise in the field of view.

V. SOURCE CONFIGURATION

Historically, holographic and irradiance correlation schemes have utilized different source configurations, in that a distinct reference wave has been present in holographic constructions. In part, the reason for this is that extraterrestrial objects are generally inaccessible to source modifications. Nevertheless, with appropriate arrangement, irradiance correlation can yield the object reconstruction as can the holographic technique.

In 1963, Gamo[10] suggested a modification of the Hanbury Brown - Twiss experiment by introducing a coherent background as a means of

---

*This autocorrelator is illustrated in Reference 4, Figure 4.

[10] H. Gamo, in Proceedings of Symposium on Electromagnetic Theory and Antennas, Copenhagen, June 1962 (Pergamon, New York, 1963), p. 809.

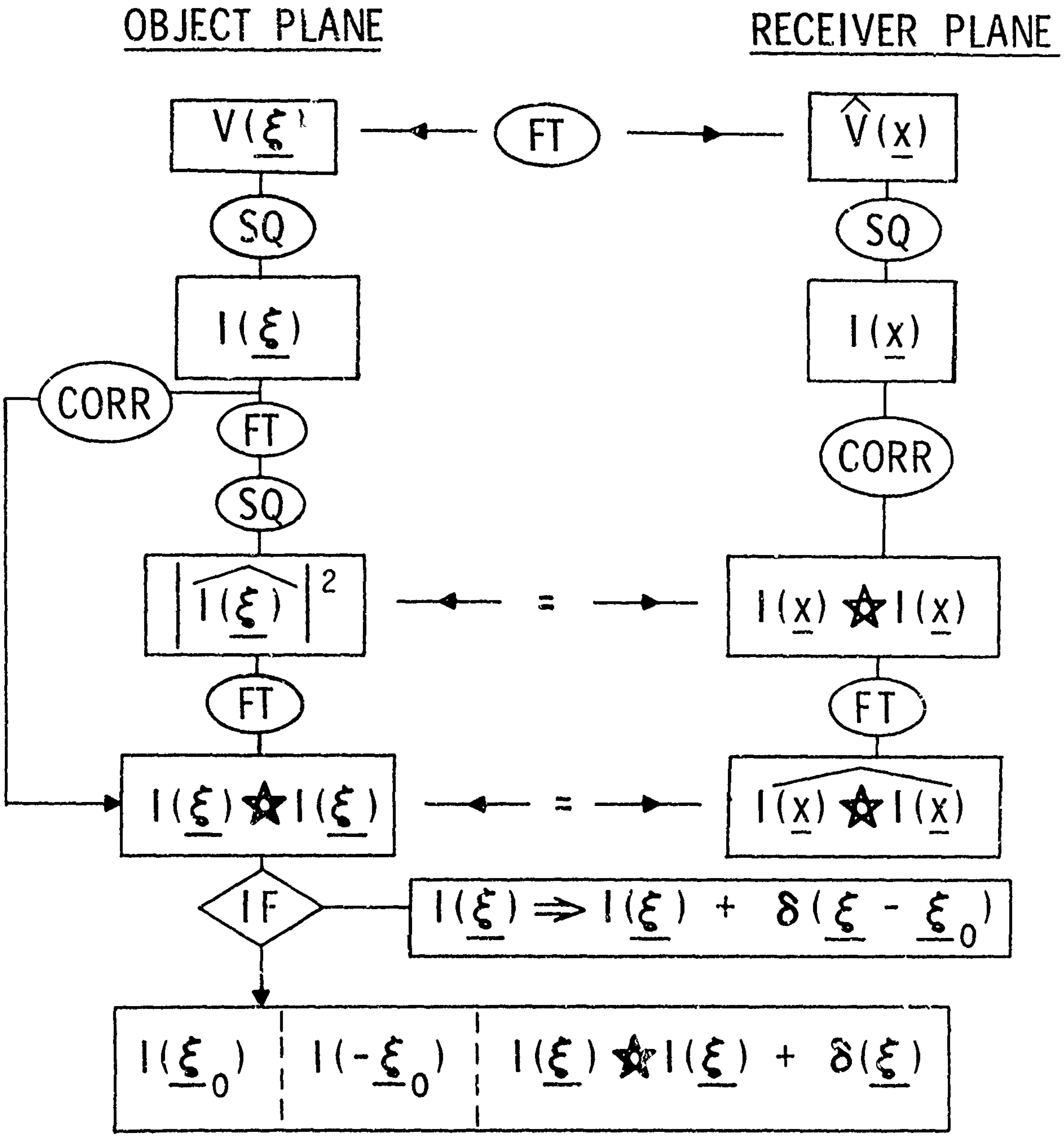

Figure 4. Mathematical relationships of irradiance correlation. CORR (and ☆) represents correlation; the other labels same as in Figure 3.

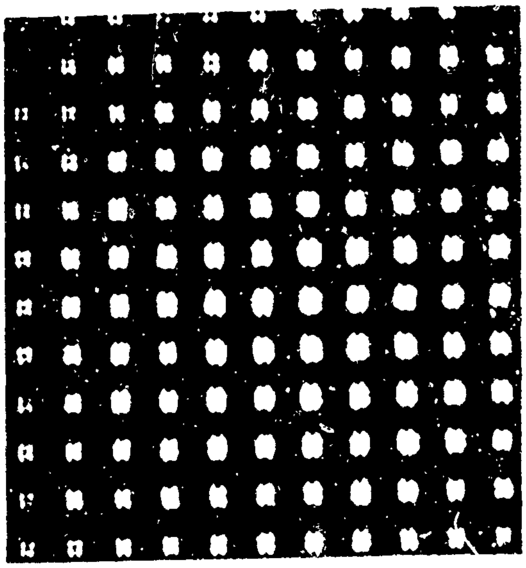

Figure 5a. Image of crossed Ronchi rulings used for object detected in $\underline{u}$ plane.

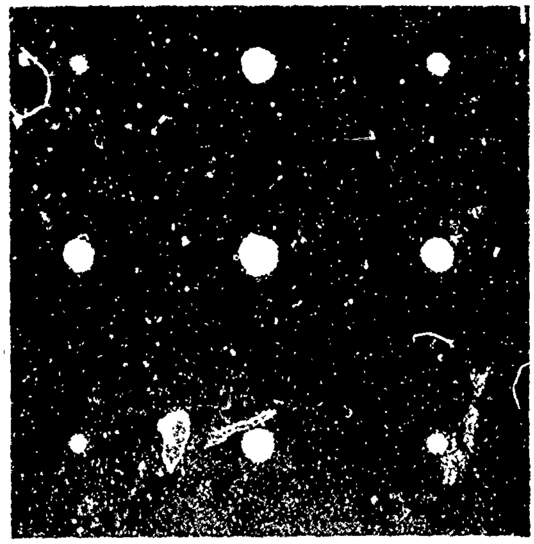

Figure 5b. Spatial power spectrum of object in a.

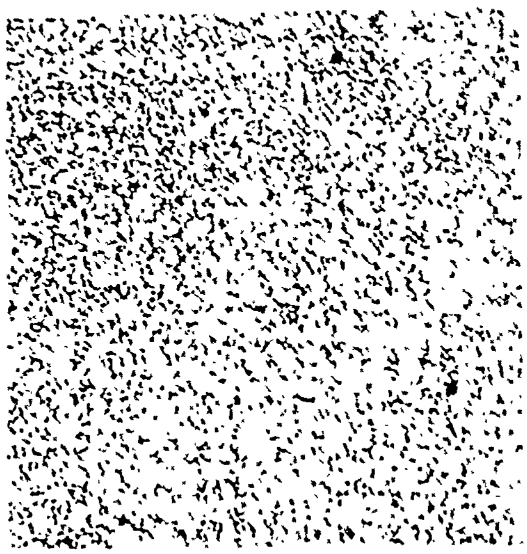

Figure 6a. Speckle pattern of object of Figure 5a with ground glass when detected in $\underline{x}$ plane.

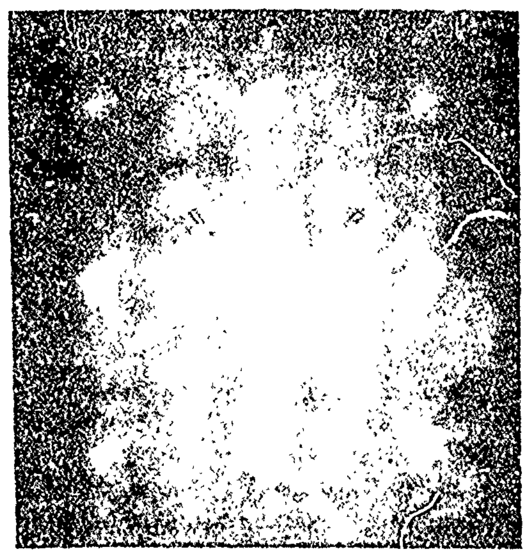

Figure 6b. Spatial power spectrum of object of Figure 5a, derived by autocorrelating speckle pattern of Figure 6a.

deriving the phase of the object Fourier transform. Later, Mehta[11] proposed that if a beam of arbitrary but known coherence properties were superimposed on the signal beam, the phase could be inferred as well.

Shortly thereafter, Beard,[9] in the experiment mentioned earlier, utilized a point reference near the object to record a signal that is the equivalent of the function shown in Figure 6b. He then coherently transformed the film record to derive the autocorrelation of the object scene. Because the object scene consisted of a point reference and the object to be reconstructed, the final display was formed of four terms, which are indicated schematically in the final block of Figure 4. For zero shift of the spatial-correlation function in the object plane, a delta function appears on the axis, surrounded by the autocorrelation of the object radiance. This is the result that is normally derived by irradiance correlation if no point reference is used. However, for larger spatial lags, the object radiance distribution appears symmetrically about the origin.

Therefore, given the presence of a point reference in the object scene, the Fourier-transform holographic and irradiance-correlation schemes give nearly identical signals. The only difference is that the holographic technique gives the square of the object-field convolution about the origin, whereas the irradiance correlation gives the autocorrelation of the object radiance, a potentially more useful quantity. It is doubtful whether, given the criterion of spatial incoherence, the former function would have any utility.

Kohler and Mandel,[12] in a study of phase inference from measurement of only the modulus, discussed the Beard experiment and gave the criterion for the minimum separation of the point reference from the object. This criterion is fundamentally equivalent to the minimum reference angle calculated by Goodman[13] for holographic imaging such that the low-frequency and the sideband information do not overlap.

Recently Deitz and Carlson,[14] in a approach not yet experimentally verified, suggested the use of beam symmetrization before speckle detection, to derive the object scene by measurement of the object power spectrum alone. In this scheme, the effect of symmetrization is to construct a pair of objects about the system origin, analogous to the results of the Fourier-transform holographic and Beard irradiance-correlation schemes.

---

[11] C. L. Mehta, J. Opt. Soc. Am. 58, 1233 (1968).

[12] D. Kohler and L. Mandel, J. Opt. Soc. Am. 63, 126 (1973).

[13] J. W. Goodman, Introduction to Fourier Optics (McGraw-Hill, New York, 1968), p. 213.

[14] P. H. Deitz and F. P. Carlson, J. Opt. Soc. Am. 64, 11 (1974).

VI. PROPAGATION THROUGH RANDOM MEDIA

Quite early, the method of irradiance correlation was investigated because of the need to minimize the effects of optical turbulence as well as certain problems with instrument vibration.[2] Reduction of effects of turbulence was noted in ensuing experiments, but the quantitative and qualitative nature of the reduction was never examined.

Beran and Parrent[15] proposed a simple analysis showing that, given pure phase modulation of the electric field by a random medium, the fourth moment is completely unaffected. The reason for this behavior becomes obvious when it is realized that the fourth-order process must be phase insensitive, because it is proportional to the absolute square of the second-order correlation (mutual coherence function) and thus does not measure phase modulation.

In the work discussed earlier, Gamo[10] realized that, if an irradiance-correlation experiment were performed with a point reference located outside the atmosphere, the results would be relatively insensitive to the effects of turbulence. Later, Beard and Barnoski,[16] using the quasithermal-source and temporal-averaging approach in an irradiance correlation experiment, showed that a pair of point sources could be detected through a random phase screen.

To illustrate the insensitivity of the fourth-order process to random phase modulation, a section of clear glass was sprayed with clear lacquer to form a random phase screen. This screen was then placed 2.5 cm before the lens in Figure 1. For comparison, a normal image of the crossed Ronchi rulings of Figure 5a was recorded in the u plane, by use of laser radiation and is shown in Figure 7a. This image was then coherently transformed as before, to compute the spatial power spectrum of Figure 7b. It is obvious from this record that the information is seriously distorted and bears little resemblance to the spectra of Figures 5b and 6b. Next, keeping the phase screen at the same location, the speckle pattern was detected at the lens plane and is shown in Figure 8a. That the radiance of this pattern is drastically modified can be observed by comparison with Figure 6a. However, following autocorrelation, the spectrum shown in Figure 8b was derived; although the signal is noisy, the spectral components adjacent to the dc signal can be clearly distinguished.

The term speckle is also used to describe an astronomical image-detection and processing scheme suggested by Labeyrie.[17] In this approach, a telescope is used to take a series of photographs that

---

[15] M. J. Beran and G. B. Parrent, Jr., Theory of Partial Coherence (Prentice-Hall, Englewood Cliffs, NJ, 1964), p. 173.

[16] T. D. Beard and M. K. Barnoski, J. Appl. Phys. 41, 4927 (1970).

[17] A. Labeyrie, Astr. and Ap. 6, 85 (1970).

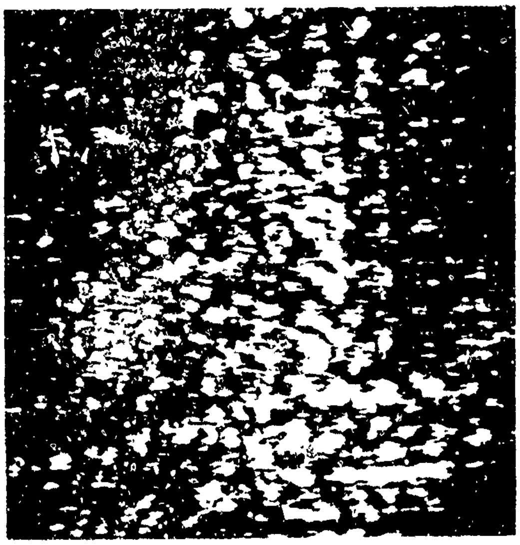

Figure 7a. u plane image of Ronchi rulings when random phase screen is located 2.5 cm before lens plane.

Figure 7b. Spatial power spectrum of Figure 7a.

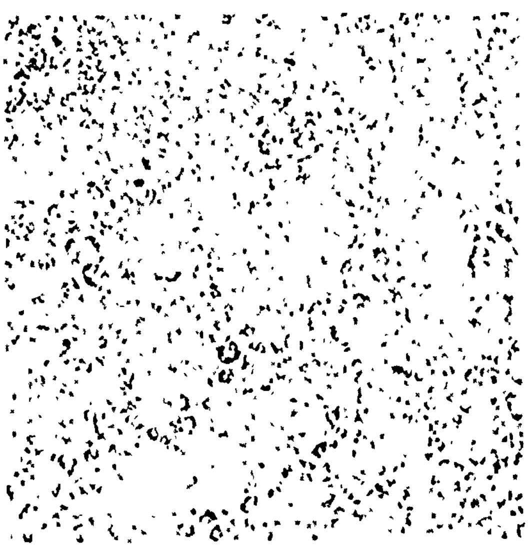

Figure 8a. Speckle pattern in the lens plane when random phase screen is in place 2.5 cm in front of lens plane.

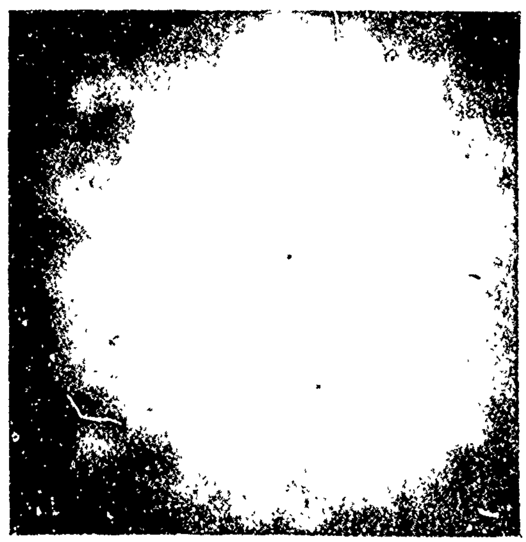

Figure 8b. Spatial power spectrum of object of Figure 5a derived by autocorrelating speckle pattern of Figure 8a.

resolve the temporal variations in the turbulence. Even though the objects being photographed are spatially and temporally incoherent, the net gain of coherence due to propagation (*vis-a-vis* the Van Cittert-Zernike theorem) is sufficient to cause a speckle pattern to be impressed on the image due to the effect of the turbulence. A series of these photographs is then used to compute an average power spectrum of the object radiance* that has considerably higher spatial resolution than that associated with the long-exposure image. We mention this important technique only to delineate clearly the speckle noise that arises from the propagation effects in a random medium from the speckle signal from an object itself, associated with all of the other imaging schemes discussed in this report.

A holographic experiment was reported in 1966 by Goodman, et al.,[18] in which a Fourier-transform configuration was used, with and without a random-phase screen, to form a hologram. Although the standard imaging technique was drastically affected, the Fourier transform-configuration gave an object reconstruction only marginally worse when a hologram was made through the random-phase screen than when no phase perturbation was present during the preparation of the hologram.

Recently, Rhodes and Goodman[19] discussed the effect of redundancy in optical performance. It is clear that random phase modulation, when applied to a series of independent contributors of spatial frequency information, can lead to essentially a zero mean signal. This behavior can be recognized by observing the form of Equation (1), where $V(\underline{\xi})$ might describe the electric field in the pupil of the telescope and $V(\underline{x})$, the field at the focus (and where R_0 is changed to f, the effective focal length). The effect of random modulation due to turbulence can be accounted for by multiplying inside the integral by a random phase term $\exp[i\phi(\underline{\xi})]$. It is easy to see that the form of the integral can be drastically modified by this change of the kernel.

It is also easy to see that the merit of the irradiance-correlation schemes, as well as of Fourier-transform holography, results from signal detection in the pupil of the receiver rather that at the focus of a lens. Because the field is squared upon detection, random

---

*One member used in such an average might be represented by the signal of Figure 7b.

[18] J. W. Goodman, W. H. Huntley, Jr., D. W. Jackson, and M. Lehmann, Appl. Phys. Lett. 8, 311 (1966).

[19] W. T. Rhodes and J. W. Goodman, J. Opt. Soc. Am. 63, 647 (1973).

phase goes out immediately. It does not remain to influence the transfer of the field to the Fourier plane in the manner represented by Equation (1).*

SUMMARY

Without extensive literature citation, we have attempted to clarify what we believe to be a fundamental equivalence among a number of optical-processing schemes. Whether it be holography, irradiance correlation, or speckle interferometry, it is the irradiance distribution that is utilized; this is true whether the record be called a hologram, an irradiance signal, or a speckle pattern. Given the object scalar field distribution and the moving ground glass diffuser configuration described at the outset, (1) twin intensity detectors could be used to measure a temporal correlation signal for various separations and orientations, or (2) using a fast exposure to freeze the speckle pattern photographically, a) the signal could be autocorrelated by an incoherent optical technique, or b) coherently transformed by a holographic process. By each method the resulting signals would be essentially equivalent.

The apparent differences between these techniques stem from the manner in which each scheme was developed, with its particular method of signal processing. In the Hanbury Brown - Twiss experiment, the signals were processed temporally with no provision for spatial recording and subsequent optical processing. Because in the beginning, all of the optical sources used were temporally and spatially incoherent, the temporal resolution requirements and constraints due to noise were extremely stringent.

In holography, the source was generally considered to be purely coherent. Following the side-band construction of Leith and Upatnieks, a reference wave was generally introduced at an angle with respect to the information beam. This gives an equivalence to an object with a nearby point reference, but this detail of object preparation can be applied to other processing schemes, as Beard has shown. Finally, in speckle correlation, a laser has been used to form a spatial pattern of detection. This is merely a hologram without a reference wave.

---

*In the Labeyrie method, the signal is detected in the normal image plane and then used to compute the object power spectrum. Although the final signal is identical to the result of irradiance correlation, the effect of turbulence as a noise term in the signal processing is radically different because of the transfer of the field from the pupil to the focal plane of the receiver just discussed. This fact can easily be observed by comparing the results of the signal derived from processing one sample from the receiver pupil (Figure 8b) with the result from processing one sample from the receiver focus (Figure 7b).

Even though the laser is often used in subsequent signal correlation, it is employed in an incoherent optical processor, and could be replaced by a thermal source.

In part, the spatial processing schemes tend to be conditioned by demands intrinsic to the construction methods. Because in spatial-irradiance correlation (speckle correlation) there is often no reference wave, the side-band modulation is absent; therefore the spatial bandwidth of the information is within the capacity of an incoherent-processing system. However, in holographic schemes, the side-band modulation sometimes demands a coherent-processing approach (as can be seen from the resolution requirements of the film).

Finally, that each of these processes should be insensitive to phase modulation in transmission can be easily understood, because each is detected in fundamentally the same fashion: a mapping of irradiance is detected in the far zone of the object. Each process is thus differential and involves spatial beats, given identical phase shifts due to turbulence, the irradiance signal remains unaffected. After detection, the method of processing depends substantially on the signal-bandwidth requirements and the predilection of the researcher.

ACKNOWLEDGEMENTS

The author thanks K. E. Joel for the optical processing reported in Figures 5-8. The author also gratefully acknowledges many helpful conversations with N. A. Peppers.

REFERENCES

1. D. Gabor, Nature 161, 777-778 (1948).

2. R. Hanbury Brown and R. Q. Twiss, Nature 177, 27 (1956).

3. W. Martienssen and E. Spiller, Am. J. Phys. 32, 919 (1964).

4. L. E. Goldfischer, J. Opt. Soc. Am. 55, 247 (1965).

5. J. W. Goodman, J. Opt. Soc. Am. 60, 506 (1970).

6. E. N. Leith and J. Upatnieks, J. Opt. Soc. Am. 54, 1295 (1964).

7. J. B. DeVelis and G. O. Reynolds, Theory and Applications of Holography (Addison-Wesley, London, 1967), pp. 62-64.

8. R. Hanbury Brown and R. Q. Twiss, Proc. R. Soc. Lond. Ser. A. 243, 291 (1957). This paper appears in Coherence and Fluctuations of Light, Vol. I, edited by L. Mandel and E. Wolf (Dover, New York, 1970), Equation (A6).

9. T. D. Beard, Appl. Phys. Lett. 15, 227 (1969).

10. H. Gamo, in Proceedings of Symposium on Electromagnetic Theory and Antennas, Copenhagen, June 1962 (Pergamon, New York, 1963), p. 809.

11. C. L. Mehta, J. Opt. Soc. Am. 58, 1233 (1968).

12. D. Kohler and L. Mandel, J. Opt. Soc. Am 63, 126 (1973).

13. J. W. Goodman, Introduction to Fourier Optics (McGraw-Hill, New York, 1968), p. 213.

14. P. H. Deitz and F. P. Carlson, J. Opt. Soc. Am. 64, 11 (1974).

15. M. J. Beran and G. B. Parrent, Jr., Theory of Partial Coherence (Prentice-Hall, Englewood Cliffs, NJ, 1964), p. 173.

16. T. D. Beard and M. K. Barnoski, J. Appl. Phys. 41, 4927 (1970).

17. A. Labeyrie, Astr. and Ap. 6, 85 (1970).

18. J. W. Goodman, W. H. Huntley, Jr., D. W. Jackson, and M. Lehmann, Appl. Phys. Lett. 8, 311 (1966).

19. W. T. Rhodes and J. W. Goodman, J. Opt. Soc. Am. 63, 647 (1973).